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AN ANALYSIS OF TURBOJET-ENGINE-INLET MATCHING

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SUMMARY

A method of presenting turbojet-engine air-flow requirements and inlet-system air-flow capacities in identical though independent parametric terms is developed. The application of the air-flow representation technique to the analysis of engine-inlet matching conditions is demonstrated. Several examples are presented to illustrate the application of the method to the explicit determination of inlet geometric variations required to improve the power-plant performance of supersonic airplanes.

INTRODUCTION

Optimum performance of turbojet-powered aircraft over the whole required flight range can only be achieved if each component of the power-plant installation is operating at its most efficient condition at all times. The turbojet engine and the inlet system supplying the engine air flow constitute two of the components for which this requirement must hold.

When considered separately, the engine and the inlet have independent air-flow characteristics. These characteristics will match at some common operating point when the engine and the inlet are combined in the power-plant installation. The success of the installation will depend on the extent to which the match point coincides with an efficient inlet operating point over the entire range of flight conditions.

This report presents a method of representing inlet air-flow capacities by the same parameter used to represent engine air-flow requirements so that the determination of the inlet operation condition at the match point can be simplified. Methods for analyzing the inlet geometric variations required to improve the power-plant performance at the match point are discussed and several examples are presented to illustrate the technique.

SYMBOLS

The following symbols are used in this report:

A	flow area, sq ft
g	acceleration due to gravity, 32.174 ft/sec ²
h_1	height of cowl lip, ft
M	Mach number
m/m_c	subcritical spillage ratio
N	engine rotational speed, rpm
P	total pressure, lb/sq ft
q	dynamic pressure, lb/sq ft
R	gas constant, 53.34 ft/ ^o R
T	total temperature, ^o R
W	air flow, lb/sec
x	ramp projection distance, ft
β	angle of oblique shock
γ	ratio of specific heats, 1.4
δ	$P_2/2116$
θ	$T_2/519$
λ	angle of compression ramp
ϕ	angle from ramp tip to cowl lip

Subscripts:

c	critical
e	engine
i	inlet
s	sonic

sub subcritical
 sup supercritical
 t throat
 0 free stream
 2 diffuser outlet or compressor inlet

METHOD OF ANALYSIS

Engine air flow. - The absolute air flow through a turbojet engine is a function of the engine rotational speed and the pressure and temperature at the compressor inlet. Through the use of the dimensionless generalizing parameters θ and δ (ref. 1), the absolute air flow can be converted to a corrected air flow $W_e \sqrt{\theta/\delta}$, which to a first order becomes only a function of the corrected engine speed $N/\sqrt{\theta}$. Such a typical corrected air-flow characteristic for a turbojet engine is shown in figure 1.

If the diffusion process in the air inlet system is adiabatic, the temperature parameter θ is only dependent on the ambient temperature and the flight speed. Hence, it is possible to define the engine air-flow schedule by a plot of corrected air flow as a function of flight Mach number and altitude for a given engine-speed schedule. Figure 2 shows the resultant schedule for the engine of figure 1 operating at a constant rotational speed. In this form of presentation the engine air-flow requirements are expressed by a parameter which is independent of the pressure recovery characteristics of the inlet system to which the engine is attached.

Inlet air flow. - The absolute air flow through an inlet is, when expressed in terms of flight Mach number, stagnation temperature, and pressure,

$$W_1 = \sqrt{\frac{\gamma g}{R}} \frac{P_0}{\sqrt{T_0}} A_0 M_0 \left(1 + \frac{\gamma-1}{2} M_0^2 \right)^{-\frac{\gamma+1}{2(\gamma-1)}} \quad (1)$$

It is convenient for ease of calculation to replace the M_0 terms by the isentropic area ratio A_s/A_0 , which can be conveniently evaluated from tables such as reference 2. It is also desirable to relate the air flow through the inlet to the projected cowl-lip area A_1 . When these operations are performed for adiabatic diffusion and the air flow is corrected by the generalizing parameters, there results

$$\frac{W_i \sqrt{\theta}}{\delta} = \left[\sqrt{\frac{\gamma g}{R}} \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{2(\gamma-1)}} \frac{2116}{\sqrt{519}} \right] \frac{P_0}{P_2} \frac{A_s}{A_0} \frac{A_0}{A_1} A_i$$

or

$$\frac{W_i \sqrt{\theta}}{\delta} = 49.4 \frac{\frac{A_s}{A_0} \frac{A_0}{A_1}}{\frac{P_2}{P_0}} A_i \quad (2)$$

where A_0/A_1 is the inlet mass-flow ratio and P_2/P_0 is the over-all total-pressure ratio.

If the inlet air flow is calculated at the throat section of the inlet, it can be shown by a development similar to that used in obtaining equation (2) that

$$\frac{W_i \sqrt{\theta}}{\delta} = 49.4 \frac{\frac{A_s}{A_t} \frac{A_t}{A_1}}{\frac{P_2}{P_t}} A_i \quad (3)$$

where A_s/A_t is the area function of the throat Mach number, A_t/A_1 is the ratio of the throat area to the projected cowl-lip area, and P_2/P_t is the internal pressure recovery downstream of the throat.

It is shown in the appendix that all points on the air-flow characteristic represented by equations (2) and (3) at a given flight Mach number can be related to conditions at the critical inlet operating point (the critical point is the minimum corrected air flow at which the mass-flow ratio has its maximum value). The variation of the critical corrected air flow with flight Mach number can therefore be used to define an inlet air-flow schedule which has the same parametric form as the engine air-flow schedule of figure 2. This inlet schedule is independent of the engine schedule, however, so that a consistent, logical basis is available for analysis of the engine-inlet matching problem through superposition of the inlet and engine schedules.

Matching procedure. - The engine air-flow schedule for an altitude of 35,000 feet from figure 2 is superimposed on a typical, critical air-flow curve for a fixed-geometry inlet system in figure 3 to illustrate

the basic elements of the matching analysis procedure. The inlet lip area has been arbitrarily chosen for this example to make the engine air-flow requirements and the critical inlet air-flow capacities coincident at a flight Mach number of 1.

While the engine-inlet combination of figure 3 is operable over the whole flight range shown, the components are not well matched because the critical inlet air-flow schedule does not coincide with the engine air-flow requirements over any range of flight Mach number. In combination with the engine illustrated, the inlet operating point would be supercritical for all Mach numbers below 1.0, the mass-flow ratio would be the maximum possible with the geometric design, and the pressure recovery would be less than the critical value as determined from equation (A2) of the appendix.

At all flight Mach numbers above 1.0, the critical inlet air-flow capacity is greater than the required engine air flow and the operating point would fall in the subcritical inlet range, thus yielding the additive-drag penalties associated with subcritical flow spillage at supersonic speeds (see refs. 3 and 4). The operating mass-flow ratios of the inlet in the flight speed range can be determined from equation (A3) of the appendix provided the subcritical pressure recovery variations are known.

The effective propulsive thrust of the engine of figure 3 could be increased if the critical inlet air-flow schedule could be made to coincide with the engine air-flow schedule or to occupy some other preselected relative position. It is evident from equation (2) that the critical, corrected inlet air-flow capacity at a given flight speed can be varied by changing the cowl-lip area, the critical mass-flow ratio, or the critical pressure recovery. In the flight speed range where critical flow is governed by choking in the inlet throat, equation (3) indicates that corrected air-flow regulation can only be achieved by changes in the cowl-lip area, the throat-to-cowl-lip area ratio, or the internal pressure recovery. It is normally desirable to maintain the pressure recovery at the highest possible value at each flight speed; therefore pressure recovery is generally eliminated as a parameter for varying the critical inlet air flow.

If mechanically feasible methods of varying the cowl-lip area can be devised that will enable the desired levels of critical pressure recovery to be maintained, the matching analysis is straightforward. For any preselected variation of critical inlet air flow, the required cowl-inlet area variation can be directly calculated from equations (2) and (3). In the event that the lip-area variation causes changes in the critical mass-flow ratios, throat-to-cowl-lip area ratios, or critical pressure recovery, these changes must also be evaluated in the appropriate equations in order to select the proper cowl area variation.

In many inlet designs, changes in the cowl-lip area may not be feasible. When this is the case, the sole parameters available for regulation of the critical inlet air-flow characteristics are the critical mass-flow ratio and the throat-to-cowl-lip area ratio. These parameters can be varied by changing the projection of the compression surface relative to the cowl, by changing the compression surface angle, or by changing both quantities simultaneously.

The required critical mass-flow ratio and throat-to-inlet-area ratio schedules can be explicitly determined from equations (2) and (3) providing a cowl area is selected, a variation of critical pressure recovery is assumed, and a desired variation of critical corrected inlet air flow is specified. These schedules can then be used to ascertain required schedules of geometrical control parameters.

APPLICATION OF METHOD

The utility and application of the proposed method of analyzing the turbojet-engine-inlet matching problem will be illustrated by considering a typical supersonic-airplane installation problem. The example will not evaluate resultant power-plant forces but will indicate the pressure recoveries or air-flow spillages that will be encountered.

Inlet Assumptions

For purposes of simplicity, the inlets will be assumed to be two dimensional. Figure 4 shows the symbols used in the inlet analysis. The assumed critical pressure recoveries of the inlets at supersonic speeds are shown in figure 5. These schedules include the theoretical pressure recovery across one oblique and one normal shock and an internal pressure recovery of 0.95. At low Mach numbers where the oblique shock becomes detached from the compression ramp, the pressure recovery schedule has been arbitrarily faired along the dashed portion of the curves.

At supersonic flight speeds the pressure recovery in the subcritical flow range, in the absence of buzz, may increase slightly, decrease slightly, or remain constant at the critical value depending on the internal diffuser properties and on geometrical details. For analytical purposes the assumption that the subcritical pressure recoveries maintain the critical values at supersonic speeds is the most straightforward and will be used in the present analysis except as noted.

The subcritical pressure recoveries cannot be assumed equal to the critical values at low subsonic speeds with any degree of validity. Reference 5 gives a method for estimating the subsonic performance of

inlets having sharp, supersonic cowl lips which will be applied to the present analysis. This method assumes isentropic external flow for ratios of throat Mach number to free-stream Mach number less than 1 and conservation of stream thrust (total momentum) at ratios greater than 1. The latter condition results in apparent external pressure losses for Mach number ratios greater than 1. For the present analysis, it has been assumed that there are additional internal losses corresponding to

$$\frac{P_t - P_2}{q_t} = 0.135$$

which gives an internal pressure recovery P_2/P_t of 0.95 with choking flow at the throat. The resultant schedule of subsonic pressure recovery is presented in figure 6 as a function of the corrected inlet air flow per unit throat area.

The assumption of a two-dimensional inlet allows some of the terms in the equations of the Method of Analysis section to be expressed as functions of geometric parameters (see fig. 4). For supersonic speeds sufficiently large that the oblique shock is attached to the compression ramp, the limiting streamline will be parallel to the ramp surface and the critical mass-flow ratio in equation (2) is given by

$$\left(\frac{A_0}{A_1}\right)_c = \frac{\cot \lambda - \cot \phi}{\cot \lambda - \cot \beta} \quad (4)$$

where λ is the ramp angle, ϕ is the angle between the ramp tip and the cowl, and β is the oblique-shock angle. The variation of the shock angle with ramp angle and flight Mach number can be determined from tables or charts such as those of references 6 and 7.

The ratio of the inlet-throat area to the cowl-lip area is given by the expression

$$\frac{A_t}{A_1} = \sin \lambda (\cot \lambda - \cot \phi) \quad (5)$$

From the assumption that the internal pressure recovery is 0.95 with choking flow, the critical corrected air flow when limited by inlet choking (eq. (3)) can be simplified by using equation (5) to give

$$\left(\frac{W_1 \sqrt{\theta}}{\delta}\right)_c = 52.0 \sin \lambda (\cot \lambda - \cot \phi) A_1 \quad (6)$$

Fixed-Geometry Inlets

The critical corrected air flows for fixed-geometry inlets having 16° ramps positioned to locate the oblique shock on the cowl lip at a flight Mach number of 2.0 are shown on the upper portion of figure 7(a) together with the required air-flow schedule of the engine from figure 2 at two altitudes. In order to illustrate some of the fundamental problems of efficient engine-inlet matching, two inlets are shown. One inlet was sized to satisfy the engine requirements with critical inlet flow at sonic flight speed and altitude of 35,000 feet ($A_1 = 2.90$ sq ft). The second inlet area was chosen to satisfy the engine requirements with critical flow at a flight Mach number of 2.0 and altitude of 35,000 feet ($A_1 = 2.38$ sq ft). The pressure recoveries and subcritical spillage ratios at which the inlets would operate with the engine are shown on the lower portion of the figure.

The choice of area for the larger inlet results in 0.95 pressure recovery with no subcritical spillage at sonic velocity and altitude of 35,000 feet. At supersonic speeds, the operating point of the inlet is always in the subcritical region. From the assumption that the subcritical pressure recoveries are equal to the critical values, the pressure recovery schedule is obtained directly from figure 5. The spillage schedule is calculated from equation (A3) with the use of the relation

$$\frac{m}{m_c} = \frac{W_e \sqrt{\theta}}{\delta} \bigg/ \left(\frac{W_1 \sqrt{\theta}}{\delta} \right)_c \quad (7)$$

At subsonic speeds, the operating point for the larger inlet will fall in the supercritical range of the inlet at an altitude of 35,000 feet and in the subcritical range at sea level. From figure 6, the critical pressure recovery at M_0 of 0.8 is 0.948. With the application of equation (3), the operating pressure recovery at M_0 of 0.8 and an altitude of 35,000 feet is determined to be 0.917.

For sea-level flight conditions, the operating air flow is referred to the throat area by using the equation

$$\frac{W \sqrt{\theta}}{\delta A_t} = \frac{W \sqrt{\theta}}{\delta A_1} \frac{A_1}{A_t} \quad (8)$$

where A_1/A_t is determined from equation (5). The operating pressure recovery schedule is then read directly from figure 6.

With the smaller inlet, the operating condition is critical at a flight Mach number of 2.0 and an altitude of 35,000 feet and is

supercritical for all other flight conditions shown. The resultant pressure recovery schedule is therefore calculated from equation (A2) with figures 5 and 6 used to obtain the critical pressure recoveries at each speed.

Variable-Geometry Inlets

As indicated in the Method of Analysis section, the power-plant installation performance can be improved by introducing variable inlet geometry. Two types of geometric variation will be considered to illustrate the application of the present analysis.

Translating ramp. - If the maximum pressure recovery schedule of the 16° ramp is adequate, translation of the ramp can be employed to reduce the subcritical spillage and therefore the additive drag at supersonic speeds. For a condition of minimum drag at a flight Mach number of 2.0, the cowl-inlet area should correspond to the smaller inlet of figure 7(a) ($A_1 = 2.38$ sq ft).

By the use of equation (2), the critical mass-flow ratio schedule of the inlet can be determined over the Mach number range from 2.0 to 1.66 (at which point the oblique shock will detach) to correspond to the engine air-flow schedule at an altitude of 35,000 feet. Equation (4) can then be solved for $\cot \phi$, which is identical to the ratio of the ramp tip projection to the inlet height x/h_1 .

At Mach numbers below 1.66, equation (6) can be solved directly to give the value of x/h_1 necessary to maintain the critical inlet air-flow schedule at the required engine value.

For subsonic flight speeds at sea-level altitude, figure 7(a) indicates that low pressure recoveries are achieved with either the large or small fixed-geometry inlets. These low recoveries at low speeds result from the high corrected air flow per unit throat area and can be increased only by increasing the throat area. At zero forward speed, figure 6 indicates that the largest possible throat should be employed. With the translating ramp, this condition implies retraction of the ramp to make the minimum flow passage area equal to the cowl area. The necessary tip position can be calculated from equation (5) by setting A_t/A_1 equal to 1. (From the assumption that the minimum area is defined by a normal from the ramp to the cowl lip, the resultant tip location is inside the cowl.)

The required ramp translations and the resultant pressure recovery and subcritical spillage schedule for the assumed example are shown in figure 7(b) by the solid curves. As compared with the fixed inlets of figure 7(a), the translating-ramp inlet combines the high-pressure

recoveries of the large-area inlet and the lack of subcritical spillage of the small inlet at supersonic speeds. For subsonic cruise at an altitude of 35,000 feet the translating inlet maintains a higher pressure recovery schedule in the flight Mach number range from 0.8 to 1.0 than either fixed-geometry inlet. For sea-level flight at subsonic speeds the translating-ramp inlet gives improved pressure recoveries over the whole speed range. The take-off ($M_0 = 0$) recovery is still low, however.

Variable-angle ramp. - Another type of inlet adjustment that can be considered in an effort to improve the matched engine-inlet performance is ramp-angle variation. In this case the inlet pressure recovery schedule and the mass-flow ratio cannot be independently specified. For the purposes of the example it will be assumed that maximum pressure recovery is desired. The optimum ramp angle at each supersonic flight speed is determined from figure 5, and the resultant, operating inlet mass-flow ratio is calculated from equation (2).

With the tip projection fixed at the value required to give a critical mass-flow ratio of 1 at a Mach number of 2.0, the critical mass-flow ratio schedule of the inlet is determined from equation (4). The subcritical spillage ratio is calculated from equation (7).

The ramp-angle schedule and the resultant pressure recovery and subcritical spillage ratios are indicated on figure 7(b) by the dashed curves. The pressure recovery at sonic velocity differs depending on whether figure 5 or figure 6 is used in the determination. In this range the pressure-recovery increase for subcritical operation indicated by figure 6 has been assumed correct, and the higher recoveries from figure 6 have been presented.

Slightly higher pressure recoveries are obtainable with the variable-ramp-angle inlet than with the translating-ramp inlet in the supersonic speed range because the 16° ramp is not optimum at Mach numbers less than 2.0. In order to utilize the high pressure recoveries, however, the ramp-angle schedule does not supply the required engine air flow at critical inlet conditions so that an increasing amount of air is spilled subcritically as the flight speed is reduced. A detailed force analysis would be required to ascertain whether the resultant power-plant performance would be acceptable.

For subsonic flight speeds at sea level, the ramp angle is zero. Hence, the variable-angle ramp pressure-recovery schedule in this speed range is coincident with that obtained with the translating-ramp inlet. For either inlet an auxiliary intake might be necessary for take-off conditions.

CONCLUDING REMARKS

The proposed method of representing the engine air-flow requirements and the inlet air-flow capacities by the same parameter offers wide utility in the analysis of power-plant installations. Inasmuch as the engine and inlet characteristics are completely independent when expressed by the proposed parameter, any number of engine and inlet combinations can be readily evaluated. Supplementary information is required to complete the power-plant force analysis. This information is identical with that required by any other analysis method, however.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 14, 1953

APPENDIX - RELATION OF INLET INTERNAL-FLOW CHARACTERISTICS TO CRITICAL OPERATING CONDITION

It is shown in equation (2) that the internal-flow characteristics of an inlet can be expressed mathematically as

$$\frac{W_1 \sqrt{\theta}}{\delta} = 49.4 \frac{\frac{A_B}{A_0} \frac{A_0}{A_1}}{\frac{P_2}{P_0}} A_1 \quad (A1)$$

Typical graphical representations of the air-flow characteristics of a fixed-geometry inlet are shown in figure 8 for a range of supersonic speeds. The pressure recovery - mass-flow ratio diagram of figure 8(a) is the most widely used method of presenting inlet performance; however, the same data are represented by the pressure recovery - corrected air-flow diagram of figure 8(b).

At each Mach number the over-all air-flow characteristic of the inlet can be separated into two distinct flow regions. In one region the mass-flow ratio has a constant, maximum value for the particular Mach number (fig. 8(a)) and the corrected air flow is inversely proportional to the pressure recovery (fig. 8(b)). This portion of the air-flow characteristic is defined as the supercritical flow region of the inlet. The point at which the pressure recovery is a maximum in the region of constant mass-flow ratio (fig. 8(a)) or, equivalently, the minimum corrected air flow for which the mass-flow ratio has a maximum value (fig. 8(b)) is termed the critical operating point of the inlet. The pressure recovery at the critical point is defined as the critical pressure recovery of the inlet.

Since the mass-flow ratio is constant at the critical or maximum value throughout the supercritical region, all points on the supercritical portion of the characteristics can be related to the critical conditions by the equation

$$\left(\frac{P_2}{P_0}\right)_{\text{sup}} = \left(\frac{P_2}{P_0}\right)_c \frac{\left(\frac{W_1 \sqrt{\theta}}{\delta}\right)_c}{\left(\frac{W_1 \sqrt{\theta}}{\delta}\right)_{\text{sup}}} \quad (A2)$$

When, by reason of a flow constriction downstream of the inlet, the inlet mass-flow ratio in equation (A1) is less than its maximum

value for a particular flight Mach number, the flow region is defined as subcritical. In this flow region the variation of pressure recovery with mass-flow ratio or corrected air flow depends upon the flight Mach number and the geometric details of the inlet design as illustrated in figure 8, and it is impossible to relate subcritical flow conditions to critical conditions by only two variables. However, from equation (A1) a general relation of subcritical and critical conditions is given by

$$\frac{\left(\frac{W_1 \sqrt{\theta}}{\delta}\right)_{\text{sub}}}{\left(\frac{W_1 \sqrt{\theta}}{\delta}\right)_c} = \frac{\left(\frac{A_0}{A_1}\right)_{\text{sub}} \left(\frac{P_2}{P_0}\right)_c}{\left(\frac{A_0}{A_1}\right)_c \left(\frac{P_2}{P_0}\right)_{\text{sub}}} \quad (\text{A3})$$

By the use of equations (A2) and (A3) it is possible to express all points on the internal inlet characteristic curve as a function of critical flow conditions. Thus the critical condition can effectively be used to represent the inlet characteristic for matching purposes.

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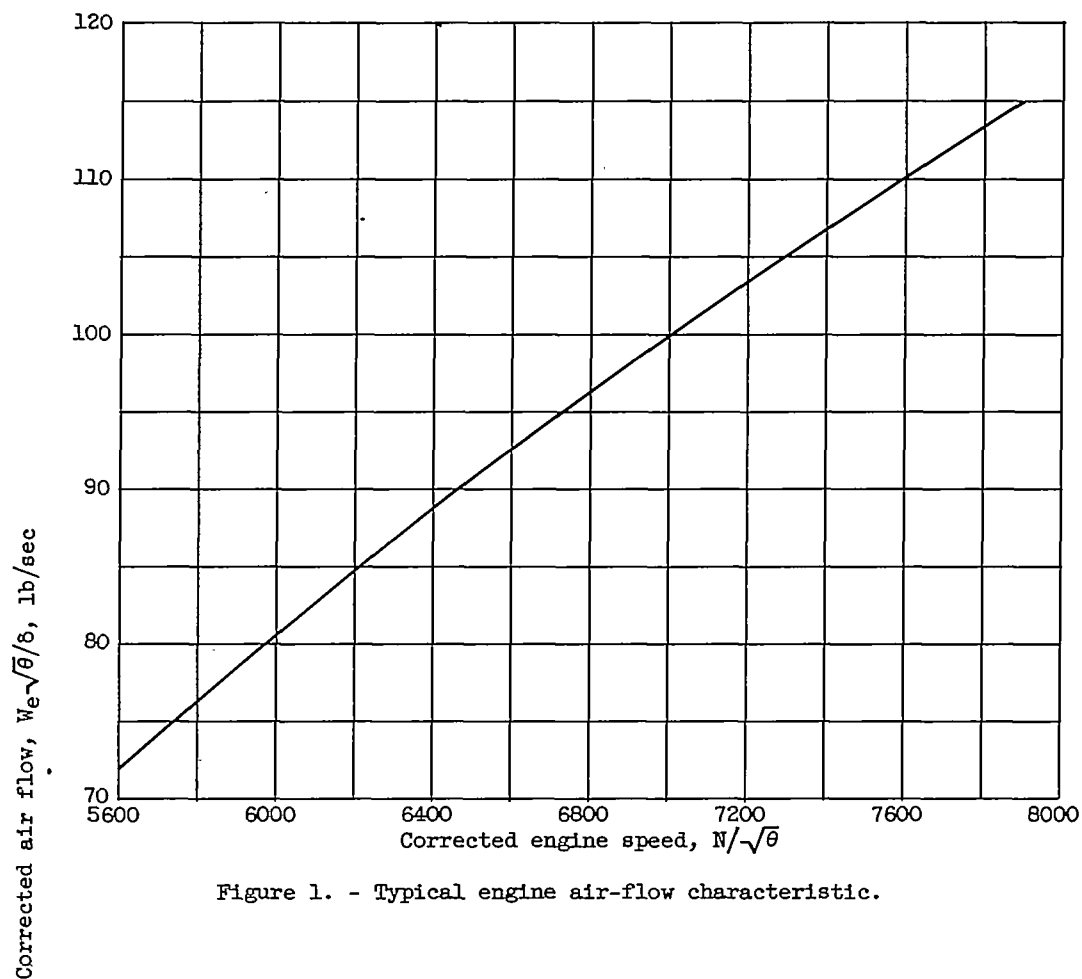


Figure 1. - Typical engine air-flow characteristic.

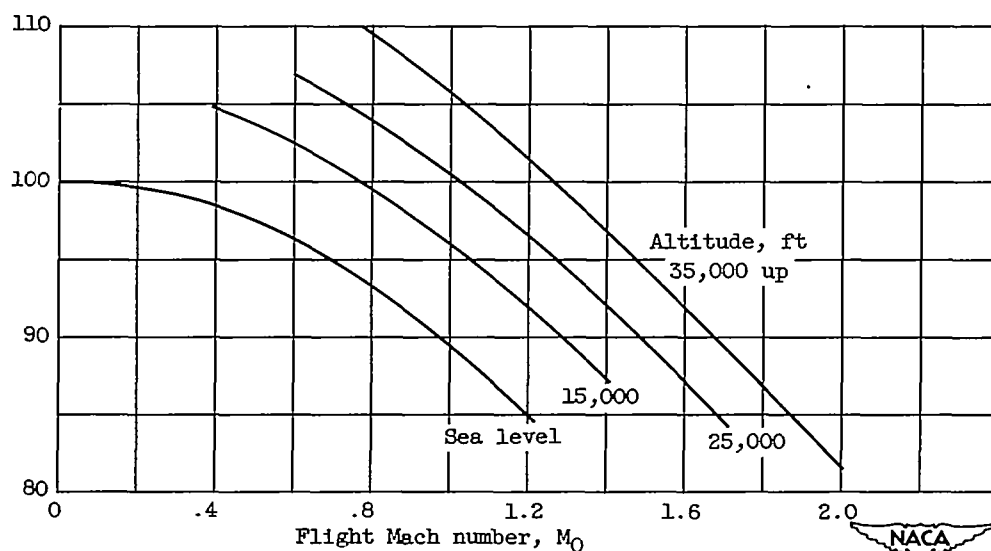


Figure 2. - Typical engine air-flow schedule. Constant engine rotational speed.

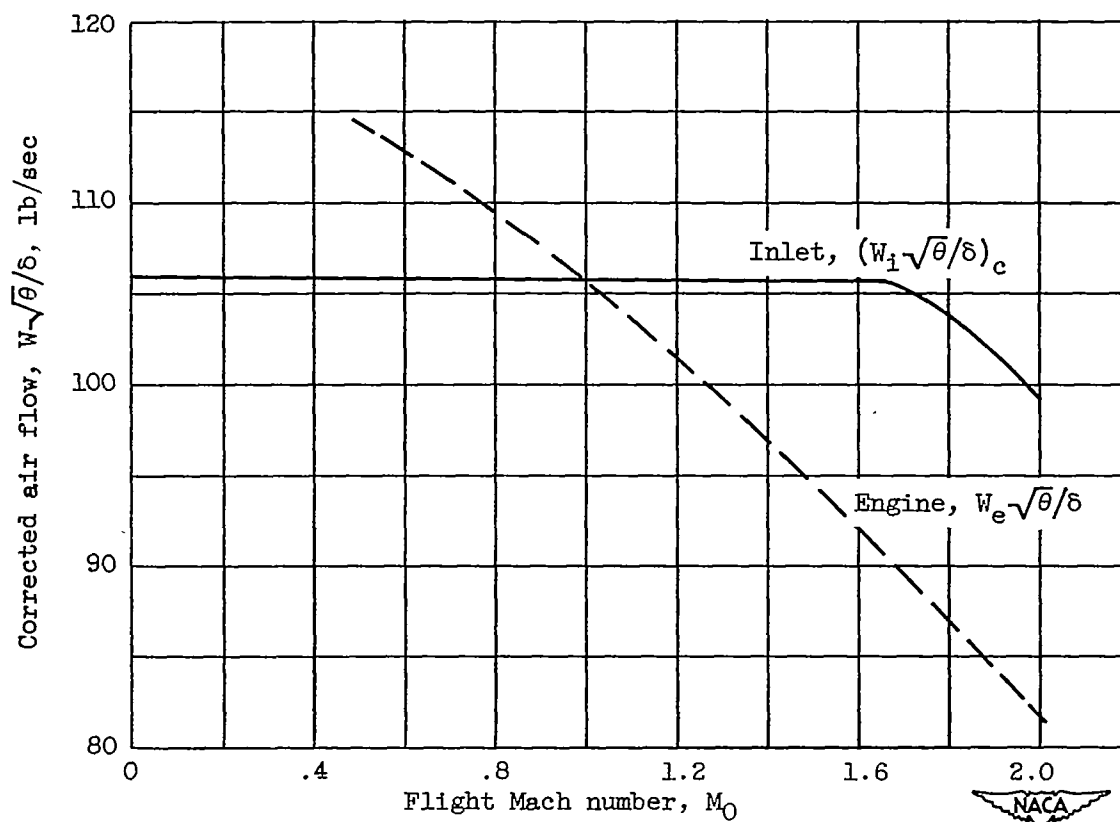


Figure 3. - Typical engine-inlet matching diagram. Altitude, 35,000 feet.

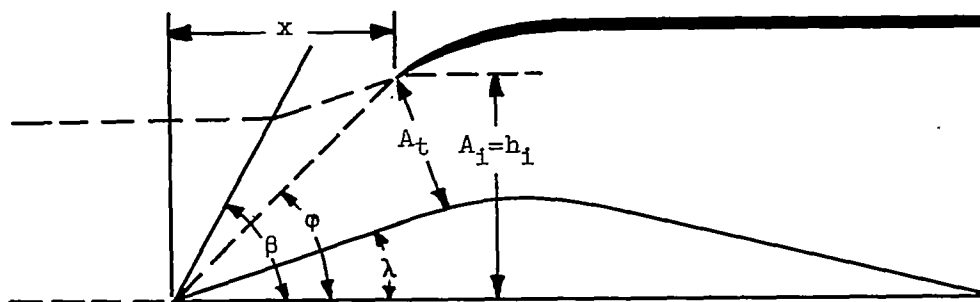


Figure 4. - Schematic diagram of two-dimensional inlet.

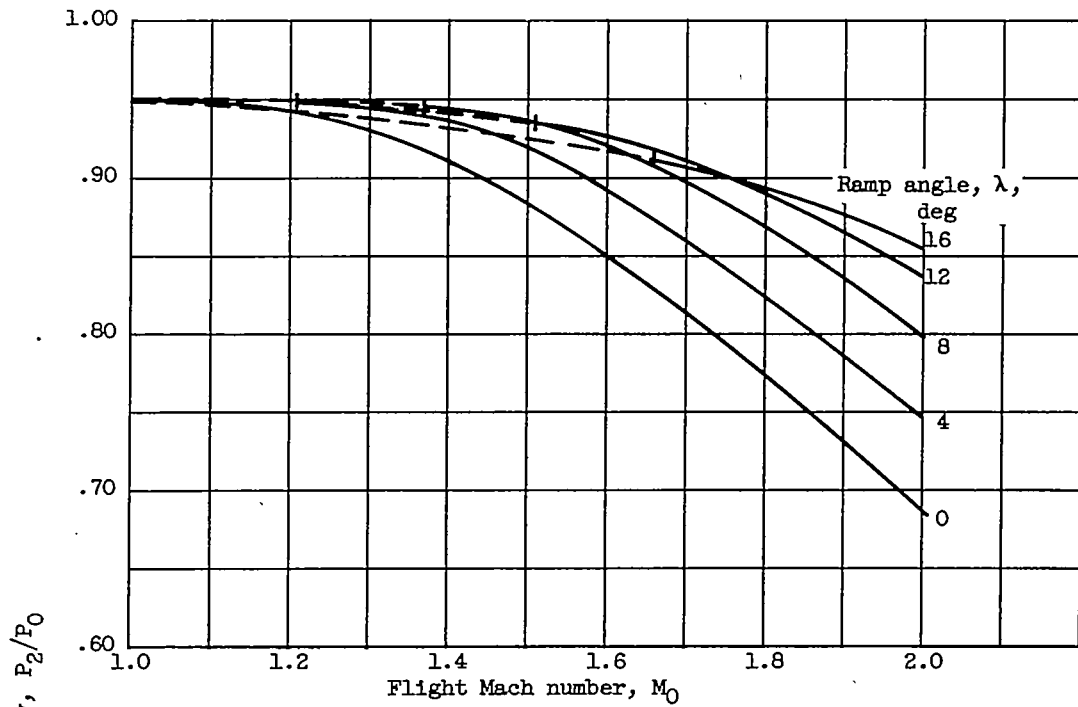


Figure 5. - Assumed critical pressure recoveries for two-dimensional inlets at supersonic speeds.

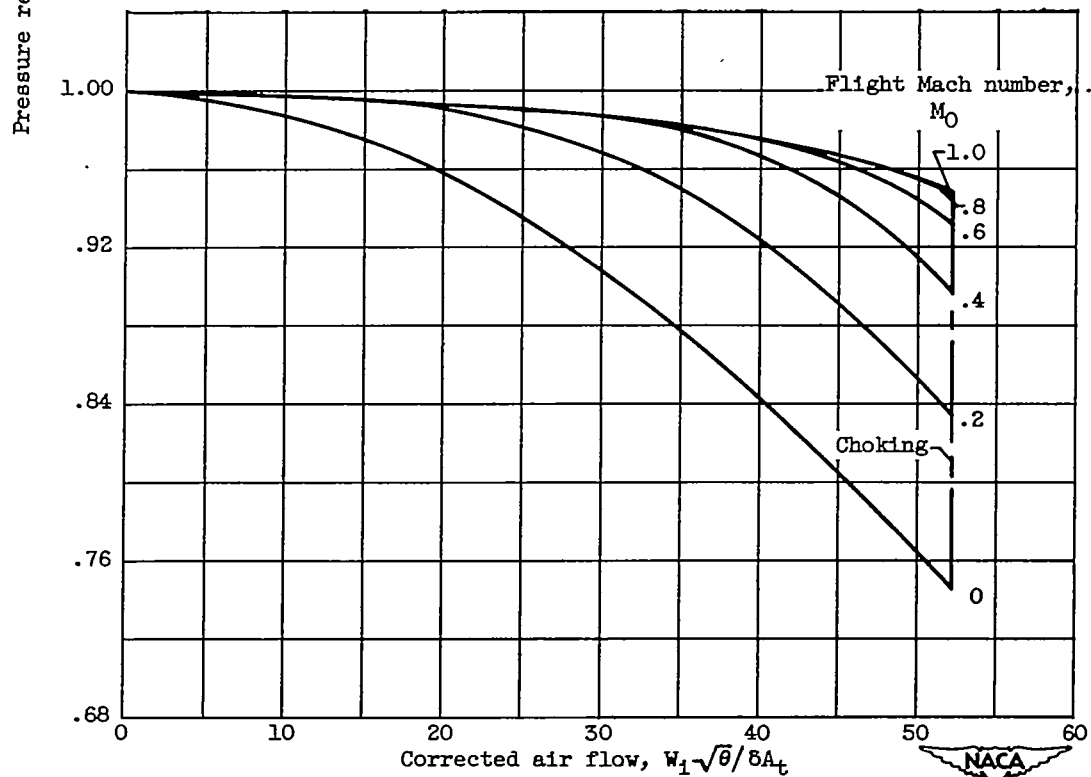
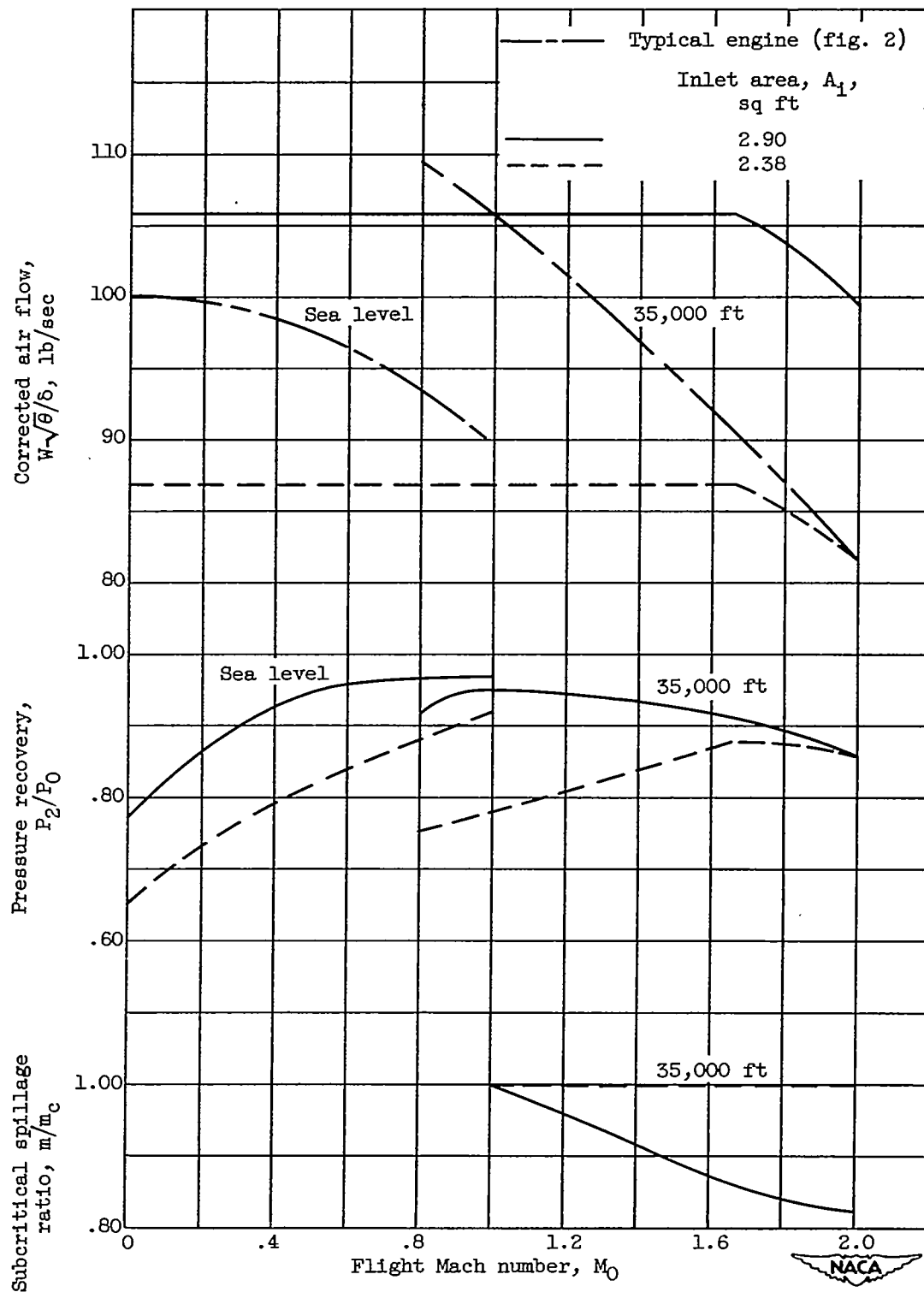
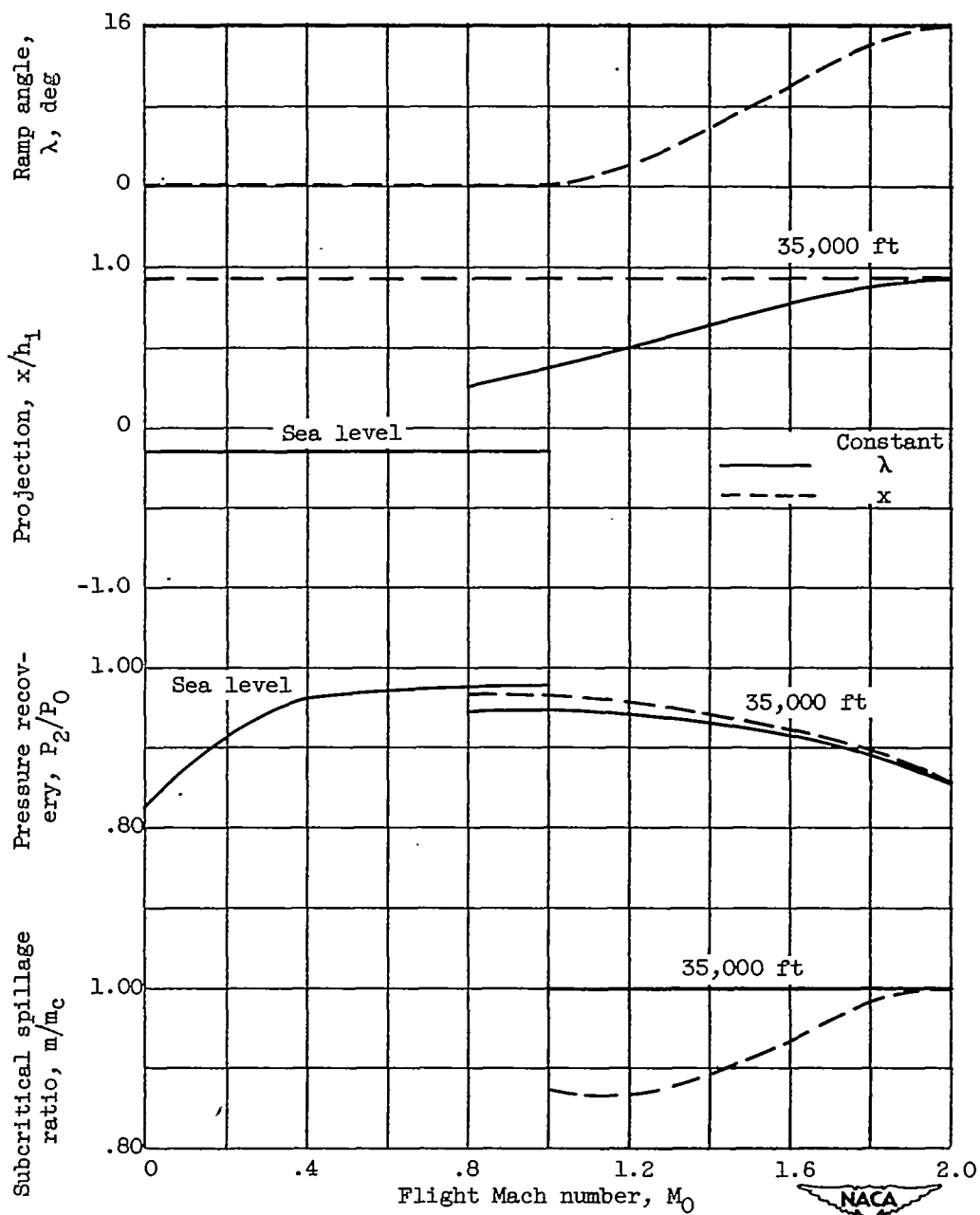


Figure 6. - Assumed subsonic pressure recoveries for sharp-lipped inlet.



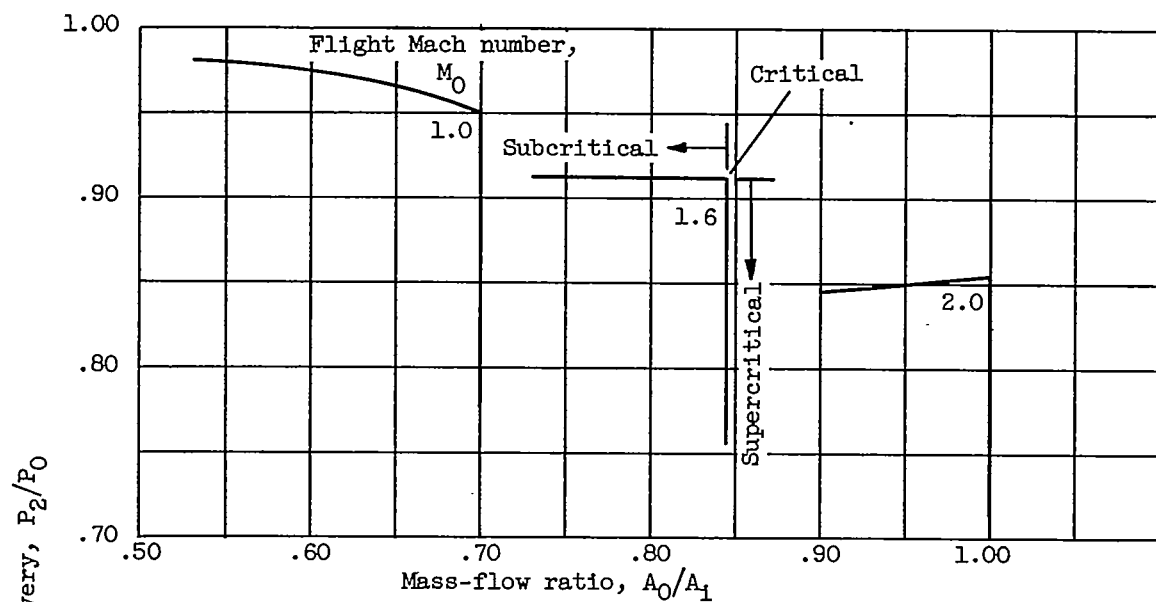
(a) Fixed-geometry inlets.

Figure 7. - Inlet matching conditions.

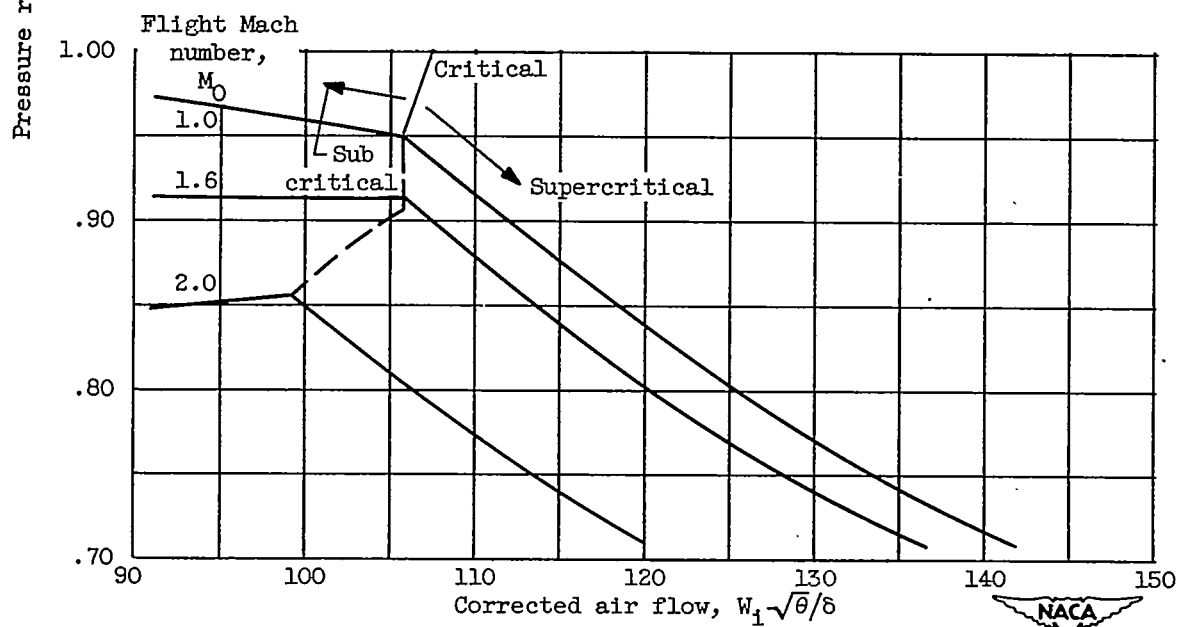


(b) Variable-geometry inlets.

Figure 7. - Concluded. Inlet matching conditions.



(a) Pressure recovery - mass-flow ratio characteristic.



(b) Pressure recovery - corrected air-flow characteristic.

Figure 8. - Typical internal-flow characteristics of fixed-geometry inlet.